Micromechanical Studies of Human Bone

Basic DOE-Supported Research Applied to Studies of Bone Damage from Aging, Injury and Disease

As reported in the March, 2003 issue of *Nature Materials*, MSD Scientist Robert O. Ritchie and his graduate student Ravi Nalla, in collaboration with John Kinney at University of California at San Francisco, have performed detailed studies that provide new insights into the mechanism of fracture in bone.

A mechanistic understanding of fracture in human bone is critical to both materials and biomedical studies of this extraordinary material. Knowledge of the structural origin of its mechanical properties is critical to our ability to create synthetic materials with those properties for non-biological applications. It is equally critical to our ability to predict fracture risk associated with age and disease and thus limit the human toll of diseases such as osteoporosis. Unfortunately, despite extensive work, a mechanistic framework for describing how the microstructure of bone affects its failure characteristics is lacking. For example, the fundamental criterion governing the initiation of fracture in bone is still poorly understood: is it controlled by the local stresses (force per unit area), or by the local strains (displacement per unit length) generated when the bone is subjected to external load. Fracture in bone has invariably been assumed to be locally "strain-controlled," but no experimental evidence has been presented to support this claim.

In the MSD work, researchers applied techniques developed with DOE support for the micromechanical study of advanced metals, ceramics and composites to the human bone studies. They prepared "double-notch-bend" geometry samples by drilling two identical notches in cadaver humerus bones. They then loaded the bone in pure (four-point) bending. Since the bending moment is identical at the two notches, when one notch breaks, the other is "frozen" on the verge of breaking, allowing an examination of where and how a crack starts (see figure). Computations of the notch-tip stress and strain fields showed that the stresses are at a maximum some distance (~ 100 microns) ahead of the notch, while maximum strains are at the notch root. Thus, a stress-controlled fracture mechanism would produce cracks that initiate ahead of the notch, while the initial fracture event for strain-controlled fracture would be at the notch.

The group showed that cracks always start at notch root, indicating that the initiation of fracture in bone is controlled by the local strains (akin to behavior in a ductile metal). The research also clarified why bone is so resilient. Researchers had thought that the microscopic (sub-micrometer) fibers of collagen in bone are what make it so tough, acting like minute bridges that span a crack (analogous to steel rods in reinforced concrete). Whereas this mechanism undoubtedly contributes to the toughness of bone, this work shows that the crack bridging occurs over longer dimensions; specifically, larger (on the scale of tens of micrometers), unbroken chunks of bone material (consisting of twisted collagen fibers) behind the tip of a crack are in fact the "workhorses" that bridge the crack, somewhat like "zipper teeth," holding it together so it doesn't rip through the material. This is termed uncracked-ligament bridging, and is shown in the figure. Further, it was found that when bone does fail, the cracks often follow osteons - microscopic channels that run lengthwise in it – thereby causing a tortuous crack path which further toughens the material. This finding could guide the design and physical properties of future implants.

This NIH study applied techniques and understanding that had been developed for the study of metals, alloys and ceramics through many years of support from the DOE Materials Sciences Division. It demonstrates that these techniques can successfully be applied to the study of biological materials as well, and to biomedical advances that can mitigate the effects of injury, aging and disease.

R. O Ritchie (510 486-5798), Materials Sciences Division (510 486-4755), Berkeley Lab.

R. Nalla, J. H. Kinney, and R. O. Ritchie. "Mechanistic Fracture Criteria for the Failure of Human Cortical Bone." *Nature Materials* **2**, 164-168 (2003).